

Recent Result on $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

Tetsuro Sekiguchi, KEK

BNL-E949 Collaboration

BNL, FNAL, UNM, Stony Brook Univ. (USA)

Alberta, TRIUMF (Canada)

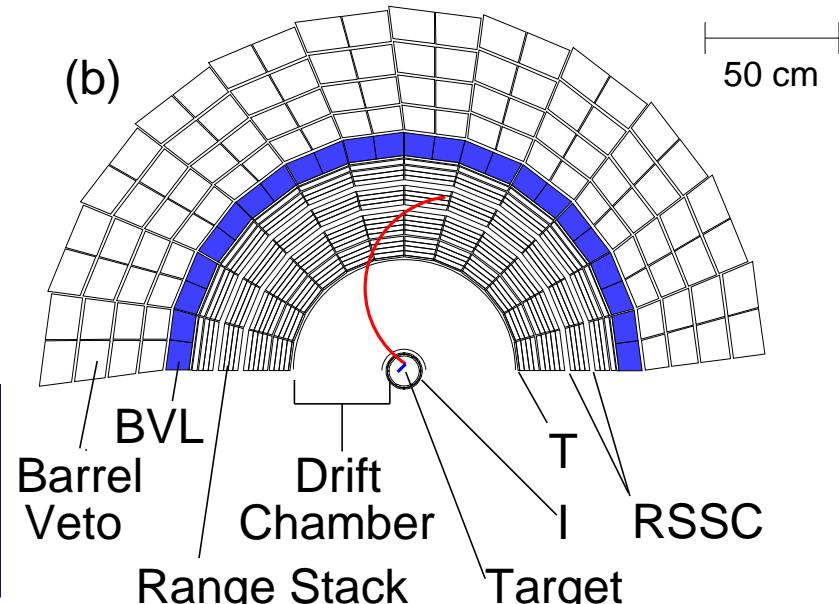
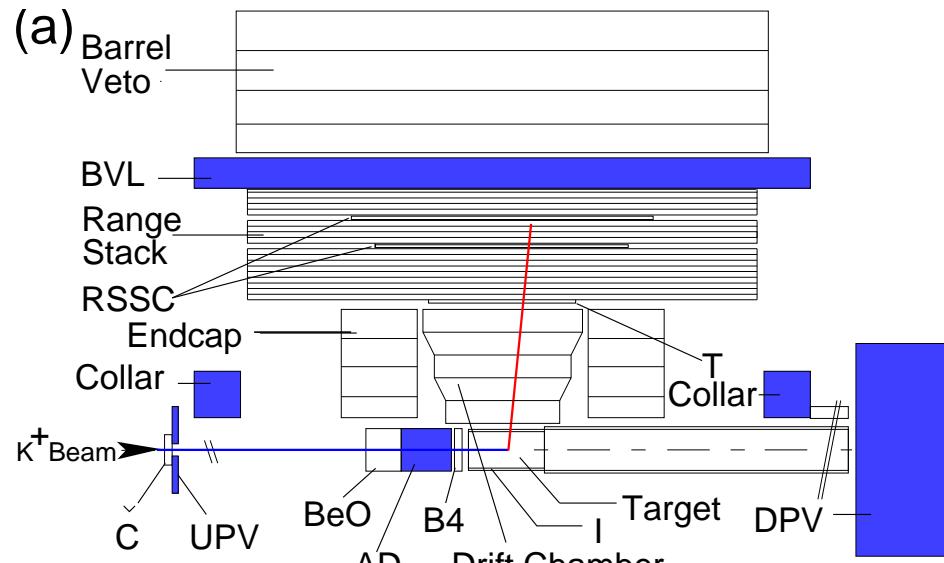
IHEP, INR (Russia)

Fukui, KEK, Kyoto, NDA, Osaka, Osaka RCNP (Japan)

- The E949 experiment
- The analysis
- The results
- Conclusions

BNL-E949 = Successor of E787

Signal = Stopped $K^+ \rightarrow \pi^+ + \text{nothing}$



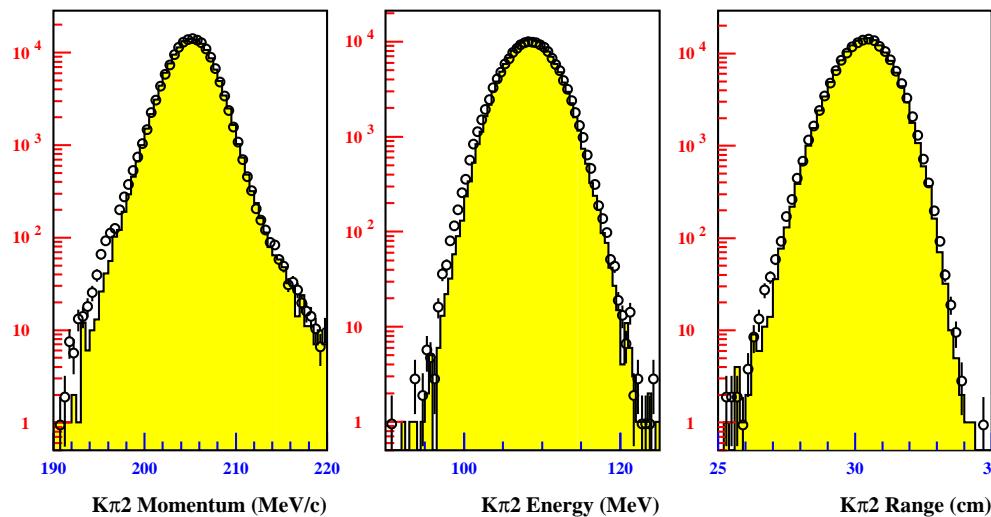
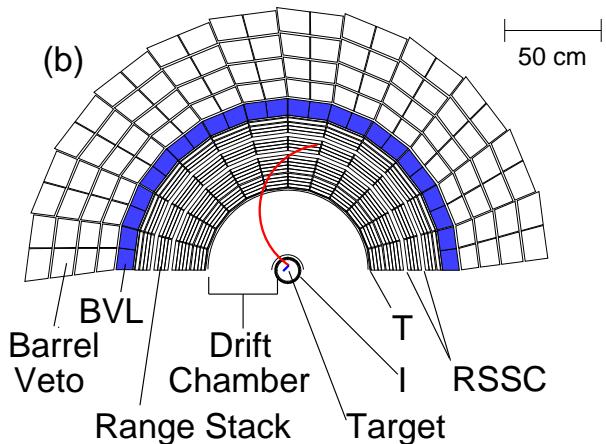
side view

end view

- Low energy K^+ beam and stop in target (intensity = $2 \times$ E787)
- Kinematics measurement \rightarrow momentum, energy and range
- $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ in the π^+ stopping counter
- Photon veto \rightarrow hermetic γ detectors

Improved kinematics measurement

Kinematics measurement is sensitive to signal selection



E787(\circ) vs E949(histo)

- RS Layer 1-5 replacement
→ more light output
- RS gain monitor system
→ better energy calibration

$K\pi_2$ Momentum, Energy and Range

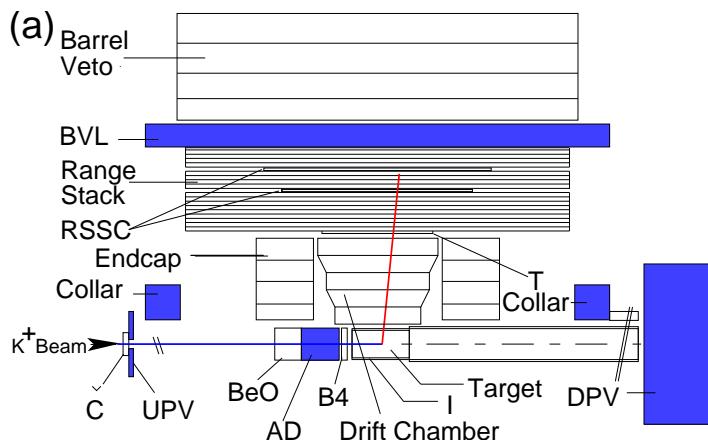
σ_P : 2.3 MeV/c

σ_E : 3.0 MeV

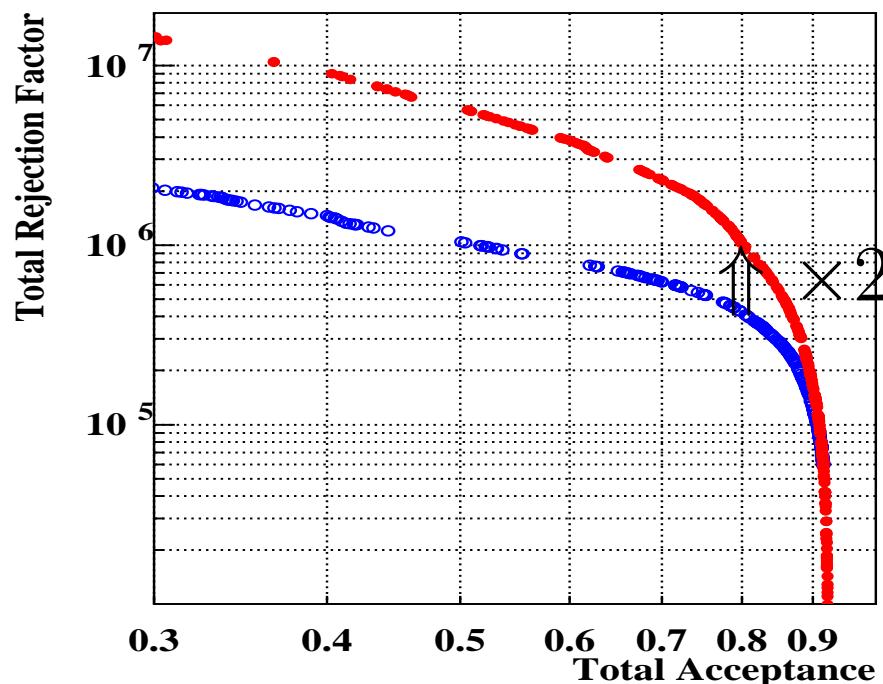
σ_R : 0.9 cm

Almost same or even better resolution with 2× detector rate

Improved photon veto



new γ detectors in blue



- new calorimeter in barrel region
→ add $2.3X_0$
- new beam line γ detectors

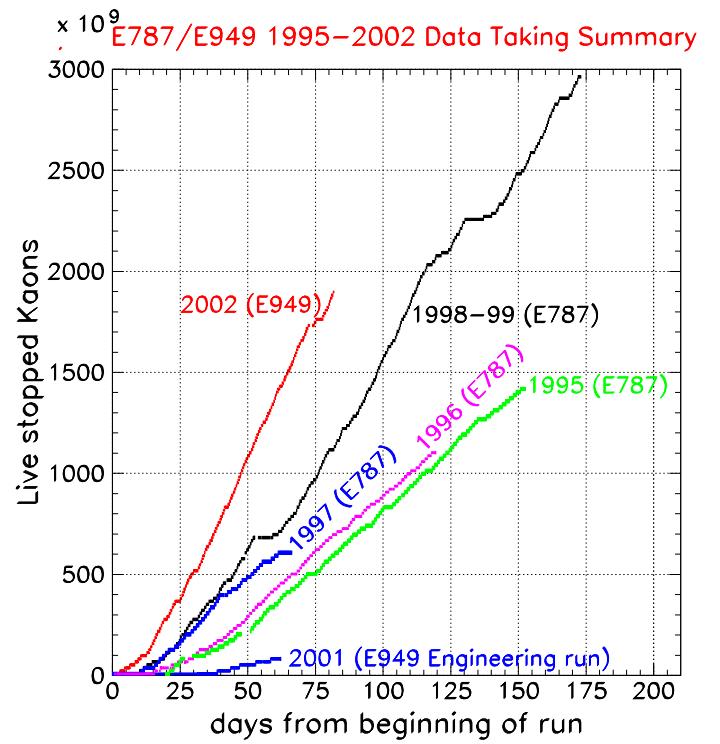
π^0 rejection

- Rejection to $K\pi_2$ background as a function of acceptance for E787 and E949.
- $\sim 2\times$ better rejection at 80% of nominal acceptance.

Data Taking

- Physics run in 2002 (12 weeks)
- $N_K = 1.8 \times 10^{12}$
- 2× intensity
- Beam condition was not optimized
- Detector worked very well
- Smooth data taking

		E787	E949
beam intensity	Tp	25-40	70
duty factor	%	52	41
K^+/π^+ ratio		4	3
N_K accumulated	10^{12}	5.9	1.8



Analysis

Signal region "the BOX"

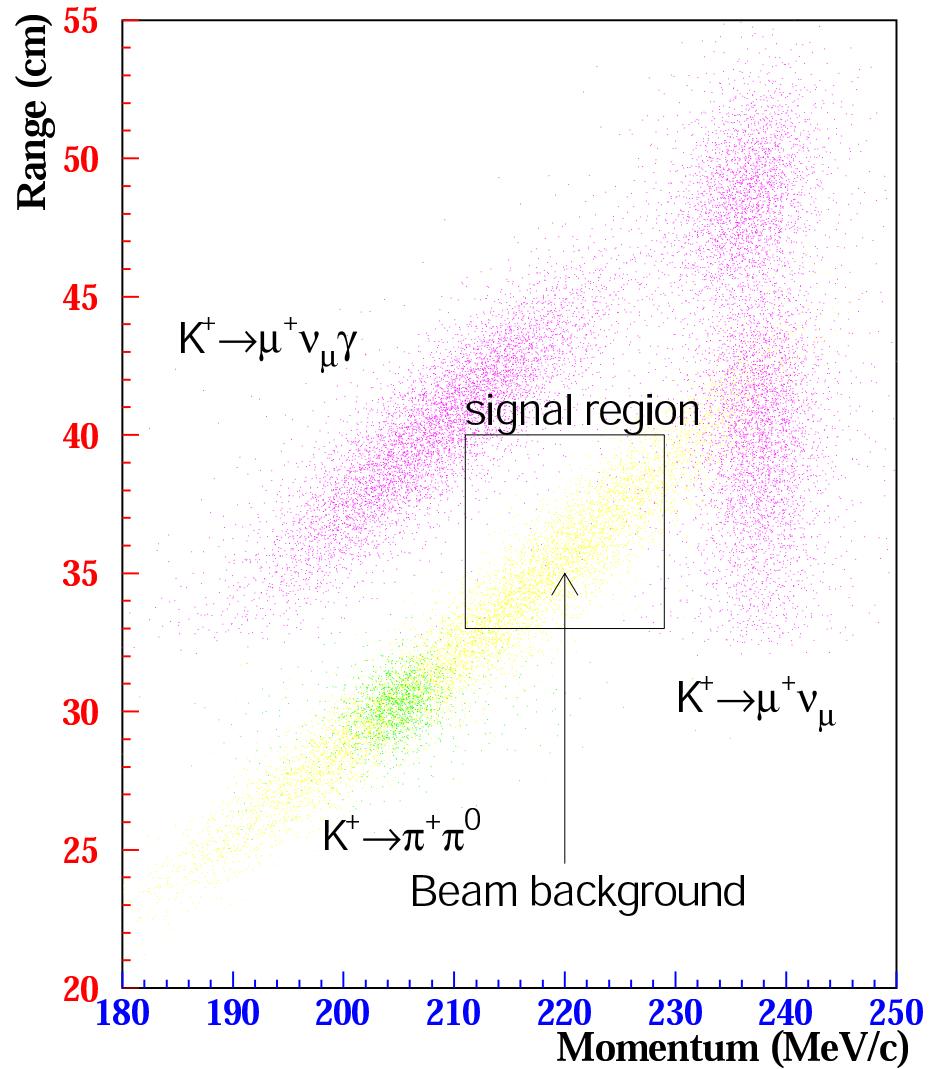
Above $K^+ \rightarrow \pi^+\pi^0$ region (PNN1)

Background sources

- $K^+ \rightarrow \pi^+\pi^0$
- Muon background ($K^+ \rightarrow \mu^+\nu(\gamma)$)
- Beam background

Analysis Strategy

- Blind Analysis
- Measure Background level with real data
- To avoid bias,
1/3 of data \Rightarrow cut tuning
2/3 of data \Rightarrow background measurement
- Characterize backgrounds using background functions
- Likelihood Analysis

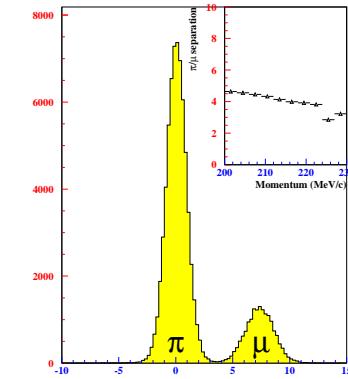


Background characterization

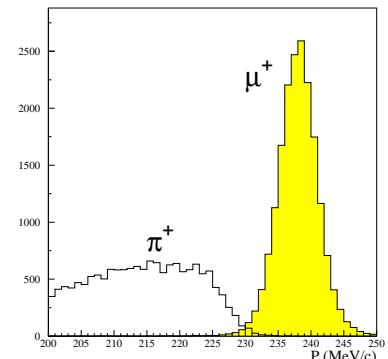
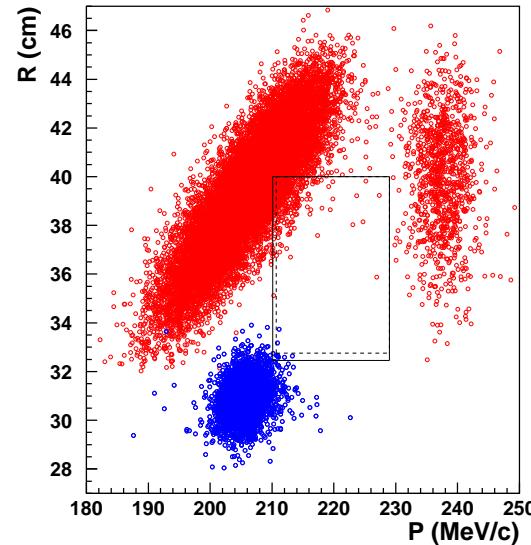
Background can be characterized using background functions

For muon backgrounds

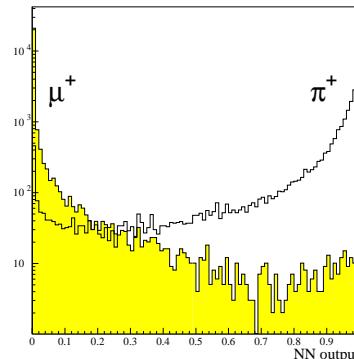
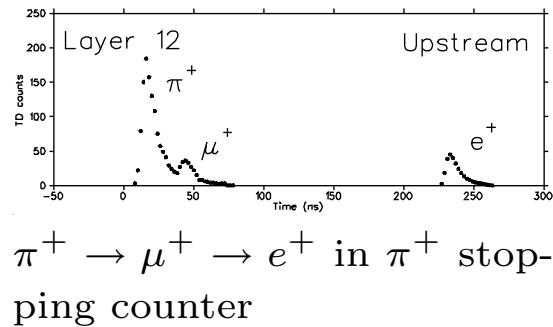
- $K_{\mu 2}$ (tail): $K_{\mu 2}$ but range is small due to interactions in the RS
- $K_{\mu m}$ (band): multibody $K^+ \rightarrow \mu^+ \nu \gamma$ decay ($K^+ \rightarrow \mu^+ \nu \gamma$, etc)



$$\chi_{rm} = \frac{R_{meas} - R_{exp}}{\sigma_R}$$



Momentum(P) for π and μ



Changing cut position

↓
Acceptance and background level
at each point of parameter

↓
Functions

Likelihood Analysis

- The search region is divided into cells.
Cell construction by binning the parameter space of the functions.

- The signal $\boxed{S_i}$ and the background $\boxed{b_i}$ in the cell \boxed{i}
 $S_i(\text{BR}) \equiv \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \cdot N_K \cdot A_i$ ($\boxed{A_i}$: Acceptance)
- The cell \boxed{i} is characterized by the signal to background ratio $\boxed{S_i/b_i}$
- **Likelihood Ratio Technique** (T. Junk: [NIM **A434**, 435 (1999)])
 - Both S_i and b_i are small \rightarrow Poisson statistic
 - The ratio of two Poisson probabilities
 - $d_i = \#$ of observed events in the cell i

Likelihood estimator

$$X(\text{BR}) = \prod_{i=1}^n \frac{\exp^{-(S_i+b_i)} (S_i + b_i)^{d_i}}{d_i!} / \frac{\exp^{-b_i} (b_i)^{d_i}}{d_i!} = \prod_{i=1}^n \exp^{-S_i} \left(1 + \frac{S_i}{b_i}\right)^{d_i}$$

$\frac{S_i}{b_i}$ of cells containing candidate events \Rightarrow Branching ratio & confidence level

Sensitivity and background

Sensitivity

	E787	E949
$N_K (10^{12})$	5.9	1.8 $\times 0.305$
Total acceptance (%)	0.20 ± 0.02	$0.22 \pm 0.02 \times 1.1$
Sensitivity (10^{-10})	0.83	2.6 $\times 0.336$

Note:

Acceptance increased by 10%
by enlarging the search region,
resulting in more backgrounds

Backgrounds

Source	E787	E949
$K_{\pi 2}$	0.032	0.216 ± 0.023
$K_{\mu 2}$	0.064	
$K_{\mu 2}$ (tail)		0.044 ± 0.005
$K_{\mu m}$ (band)		0.024 ± 0.010
Beam backgrounds	0.050	0.014 ± 0.003
Total backgrounds	0.14 ± 0.05	0.298 ± 0.026

For the likelihood analysis,
important is
the S_i/b_i ratio in each cell,
NOT the total background in
signal region

All cuts are fixed and ready to open the BOX !

Opening the BOX

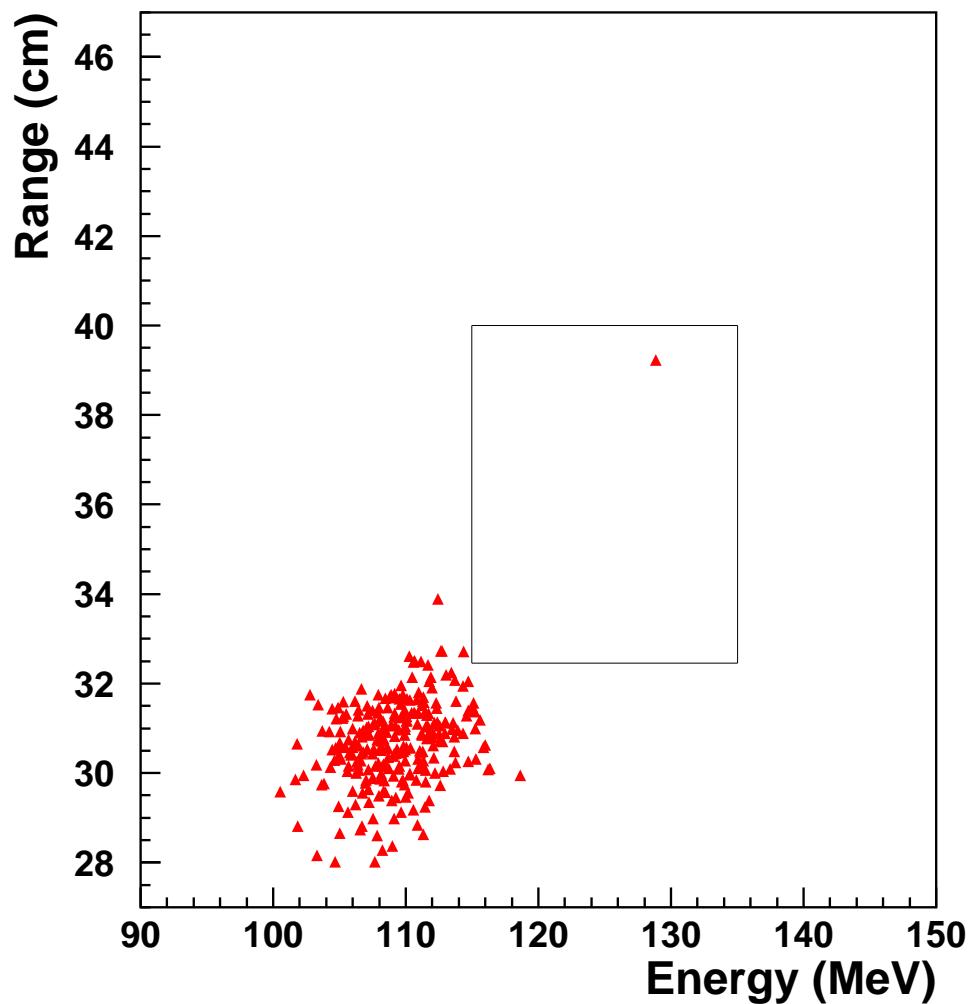
Range (cm) vs Energy (MeV) for E949
data after all other cuts applied.

Solid line shows signal region.

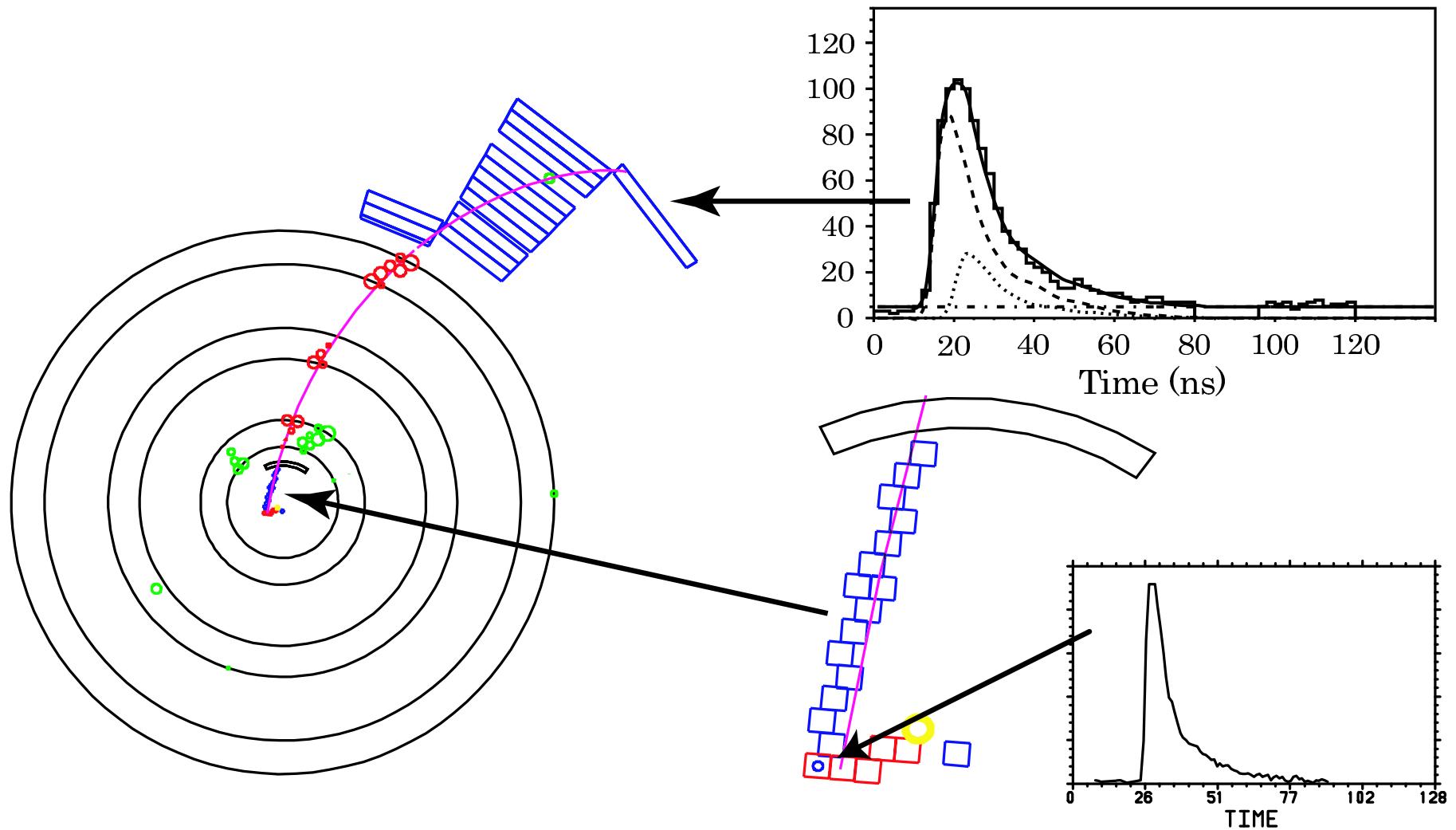
Single candidate found.

Cluster near 110 MeV is unvetoed
 $K^+ \rightarrow \pi^+ \pi^0$.

Momentum (MeV/c)	227.3
Range (cm)	39.2
Energy (MeV)	128.9
Photon	○
$K^+ \rightarrow \pi^+$ decay time (ns)	4.3
$\pi^+ \rightarrow \mu^+$ decay time (ns)	6.2
$\mu^+ \rightarrow e^+$ decay time (ns)	1370
Beam	○



Event Display



Branching ratio & Confidence level

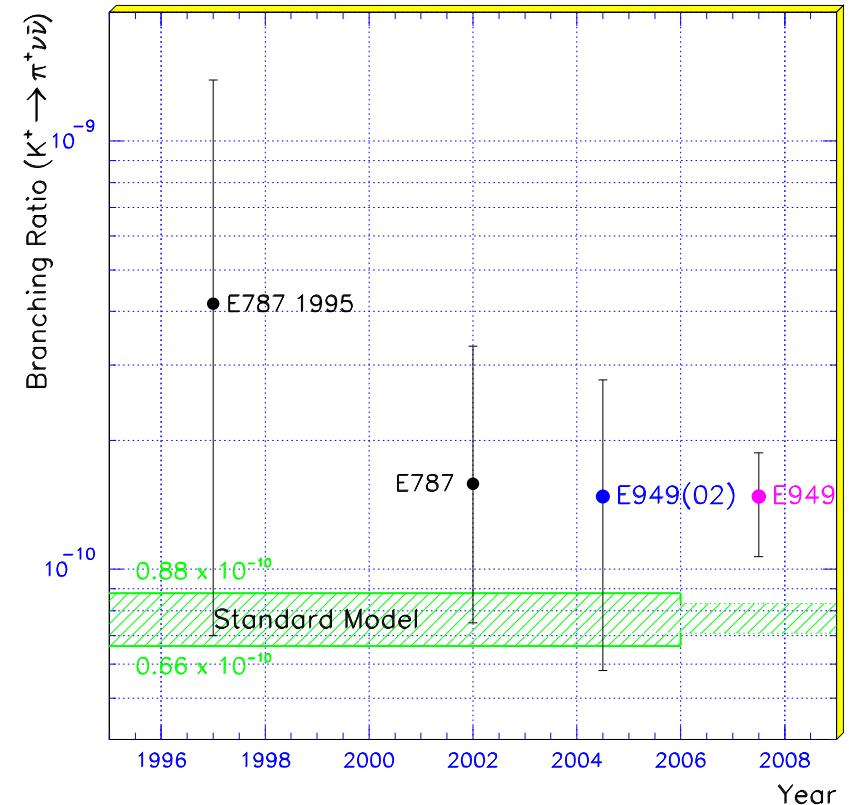
- E949 result alone:
- Combine E787 & E949 results
→ increase statistics

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$$

(68% C.L.)

	E787		E949
N_K	5.9×10^{12}		1.8×10^{12}
Candidate	E787A	E787C	E949A
S_i/b_i	50	7	0.9
$W_i \equiv \frac{S_i}{S_i + b_i}$	0.98	0.88	0.48

(W_i : signal contribution to the $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$)



E949(02) = combined E787&E949.
E949 projection with full running period.
(~60 weeks)

Conclusions

- Upgrades of E787 to E949 were successful.
- Likelihood analysis was performed to measure $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$.
- E949 has observed an additional $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ candidate.
$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$$
 (68% C.L., PNN1 region)
from the combined E787 and E949 result.
- We need more data
 - Further E949 running?
 - Analysis of "below $K^+ \rightarrow \pi^+ \pi^0$ (PNN2) region"